

A DIVER MONITOR SYSTEM

John D. M. Hamilton

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THESIS

A DIVER MONITOR SYSTEM

by

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December 1973

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A Diver Monitor System

by

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Lieutenant, United States Navy
B.A., Colgate University, 1965

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ABSTRACT

A system is presented which allows continuous monitoring of a free-swimming diver. The Diver Monitor System (DMS) employs a diver-carried acoustic transmitter which transmits pulses synchronized with the diver's heartbeat. Surface personnel are able to monitor the diver's general physical state as indicated by his heart rate and, by directional homing with Navy hand-held sonar, can locate and recover divers in zero visibility conditions. A continuous signal may be transmitted automatically in the event the diver's heart stops or exceeds preset limits.

The diver's electrocardiogram signal is picked up by chest electrodes, amplified, filtered, and waveshaped into a trigger pulse which activates a one watt 40 kHz. sonar transmitter.

The writer wishes to express his appreciation for the suggestions and assistance furnished by Max W. Lippett and J. H. Elkins of the Naval Coastal Systems Laboratory, Panama City, and to Professor George Marmont for his encouragement and guidance.

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I. INTRODUCTION

A major disadvantage of self-contained diving systems is the lack of communication between divers and tending personnel. A large measure of the safety inherent in tethered diver systems results from the continuous communication between diver and tender. The tethered diver is able to give continuous verbal indication of his situation and, in an emergency, the standby diver is able to reach him immediately by following the communication/lifeline. The self-contained diver, however, has no means of communicating with his tenders. His position is unknown to topside personnel who generally rely on visually tracking his surface bubbles (when conditions permit) to maintain a rough estimate of his position. The free-swimmer is unable to indicate an emergency situation and, even when an emergency has been recognized by his tenders, has almost no chance of being located prior to exhausting his air supply.

The psychological impact of his inability to communicate or to receive assistance can cause a diver to panic in an emergency situation. Such panic has resulted in many fatal diving accidents involving free-swimmers. If the diver had the reassurance that he was being monitored by topside, that he could indicate an emergency situation, and that he could be quickly located, he would be less likely to panic.

The system described in this thesis, the Diver Monitor System (DMS), is a diver-carried acoustic transmitter designed to provide the above capability to the untethered diver. The DMS transmits pulses synchronized with the diver's heartbeat allowing topside personnel to continuously monitor each diver's general physical state as indicated by his heart rate. If the diver gets in trouble he can signal topside by manually switching

from heart rate mode to continuous wave (CW) mode. Should the diver's heart stop or exceed preset limits, DMS so indicates to topside.

In zero visibility conditions (in which most Navy diving operations are carried out), the standby diver is able to quickly locate a DMS-equipped diver by homing on the DMS signal with hand-held sonar. The carrier frequency of the DMS, 40 kHz, is compatible with the Navy hand-held sonar now in use by diving activities throughout the fleet.

A DMS has been designed, built, and tested. It has a maximum range of 1000 yards and operates continuously for up to three hours. It is small, simple, rugged, and inexpensive. The DMS concept appears to be a practical and feasible solution to a serious problem.

II. SYSTEM PARAMETERS

Ultrasonic energy was chosen for the DMS since it provides the greatest range in water for a given transmitter power, and since it allows compatibility with present day Navy hand-held sonar.

The 40 kHz. frequency band was chosen for compatibility with hand-held sonar. It is a good compromise in terms of the propagation characteristics of water; at high frequencies excessive attenuation reduces range; at low frequencies acoustical noise in the water increasingly interferes with the received signal. Also, 40 kHz. is above the audible range and does not distract the diver.

The desired range of approximately 1000 yards was calculated as the radius a diver may swim from a point directly beneath the diver support craft.

The solution of the sonar range equation for a range of 1000 yards indicates a required transmitter power of approximately one watt. To solve the complete sonar range equation requires exact knowledge of many parameters which vary with conditions at a particular diving site. One watt was calculated using several approximations, and was chosen as a design starting point.

Other primary considerations in the design of DMS were that it be small, rugged and reliable, and constructed of inexpensive off-the-shelf components.

III. FUNCTIONAL DESCRIPTION

A. ELECTROCARDIOGRAM SECTION

Two chest-mounted electrodes pick up the diver's electrocardiogram waveform. This waveform (Figure 1) is amplified by a differential amplifier from approximately one millivolt at the electrodes to approximately 0.5 volts at the output of the differential amplifier. The differential amplifier utilizes one Fairchild uA741 operational amplifier in the configuration indicated in schematic 1, yielding a gain of 500 and a common mode rejection ratio of 77 dB. The electrodes used are commercially available silver - silver chloride ECG electrodes. Electrode paste is used between the skin and the electrode as a conducting medium.

Figure 2 is an ECG waveform at the output of the differential amplifier with the subject at rest. Figure 3 is the same subject with the same electrode placement doing pushups. The waveform in Figure 3 is the summation of the ECG waveform and the muscle-generated myoelectric waveform. The myoelectric waveform is the resultant of the muscle action potentials in the area under the chest electrodes. Myoelectric signals are typically from one to several millivolts in amplitude. Clearly, a swimming or working diver could generate myoelectric waveforms of magnitude sufficient to obscure the ECG.

A frequency analysis of ECG and myoelectric waveforms indicated a strong 20 to 28 Hz. component in the ECG, and a strong 40 to 45 Hz. component in the myoelectric. Several filters were designed, built, and tested on exercising subjects. The most successful proved to be an active Butterworth filter which was implemented in the final design. The filter is a low pass four pole design with a 28 Hz. 3 dB frequency and low frequency gain of 9.4 dB.

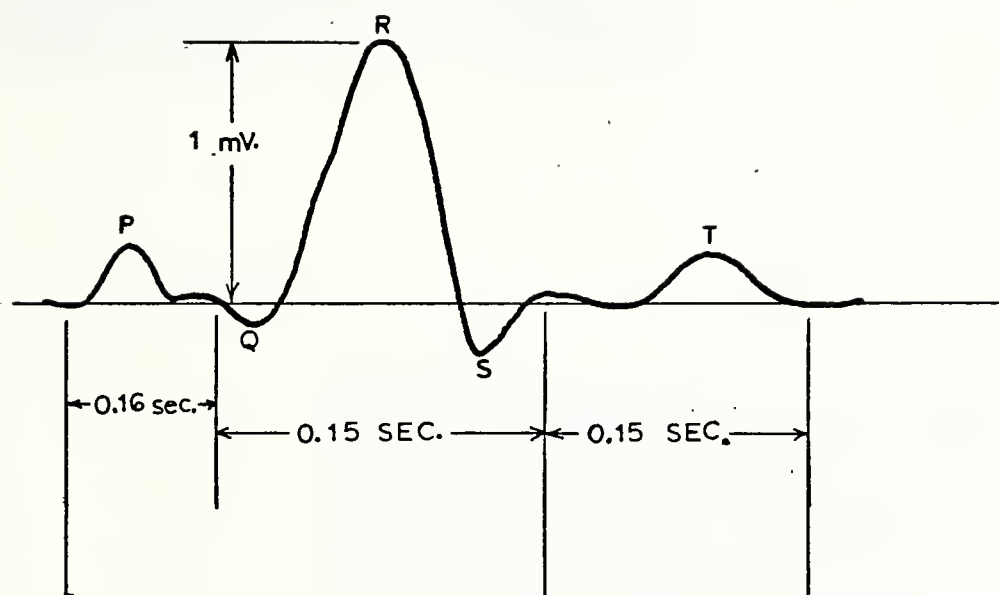


FIGURE 1
TYPICAL
ELECTROCARDIOGRAM
WAVEFORM

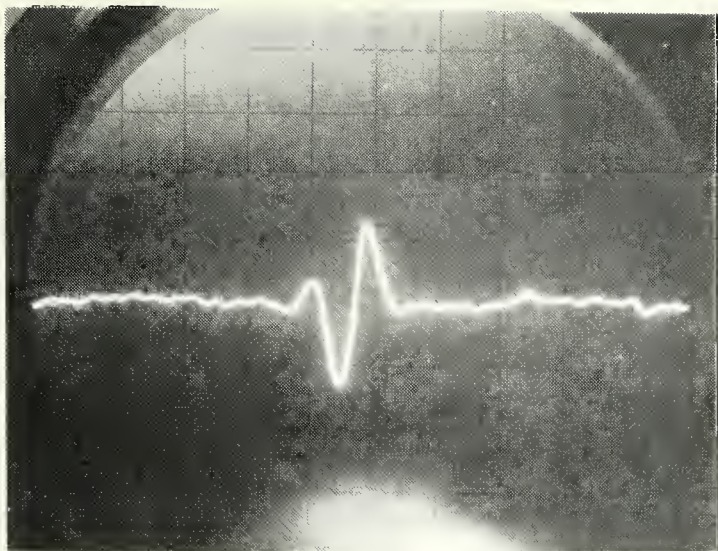


Fig. 2

0.2 sec/cm

0.2 volts/cm

modified "V5" lead configuration; lower left chest,
upper center chest

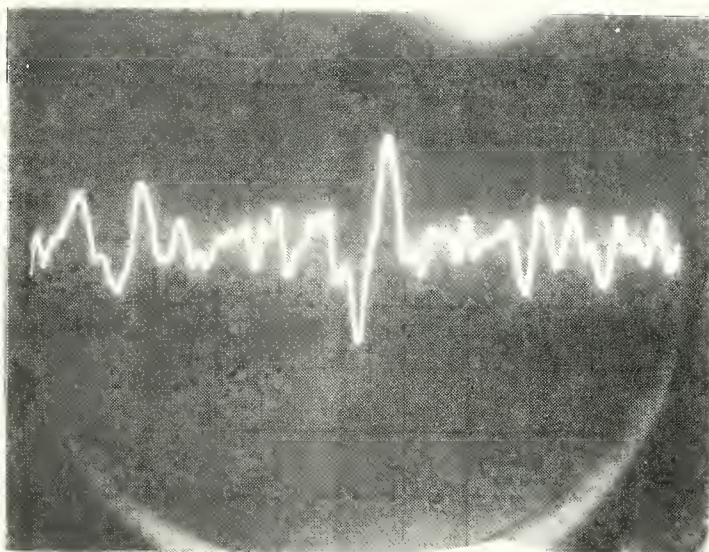


Fig. 3

0.2 sec/cm

0.2 volts/cm

modified "V5" leadoff

The filter output signal, a low pass version of the ECG with most myoelectric artifact suppressed (Figure 4), is passed through two clipping/amplifying stages to yield a clean, artifact-free pulse (Figure 5) of approximately five volts amplitude. This pulse triggers the sonar transmitter each time the diver's heart beats.

B. TRANSMITTER SECTION

The sonar transmitter consists of a 40 kHz. oscillator followed by a power amplifier stage which drives a piezoceramic transducer.

The oscillator is a Wien Bridge phase shift sinusoidal oscillator utilizing a uA741 operational amplifier. The output stage is a complementary symmetric class B transistor amplifier using a NPN and a PNP transistor. With split power supply configuration, two nine volt batteries yield a 17 volt swing across the transducer.

The piezoceramic transducer must be resonant at the input frequency. A transducer which is not resonant at a desired frequency may be tuned by adding a series inductor of the proper value which resonates with the internal capacity of the transducer at the desired frequency. An equivalent circuit of the piezoceramic transducer is presented in Figure 6.

C. RECEIVER

A commercial battery-operated receiver designed for reception of amplitude modulated acoustic signals in the 40 kHz. band was borrowed from the Naval Coastal Systems Laboratory (NCSL), Panama City, and fitted with a beat frequency oscillator for CW reception. This receiver was used throughout the project. As a continuation of the DMS project, a battery powered solid state receiver with digital heart rate counter and LED read-out is being designed by Lt. David C. Steere, USN, who is continuing the DMS project.

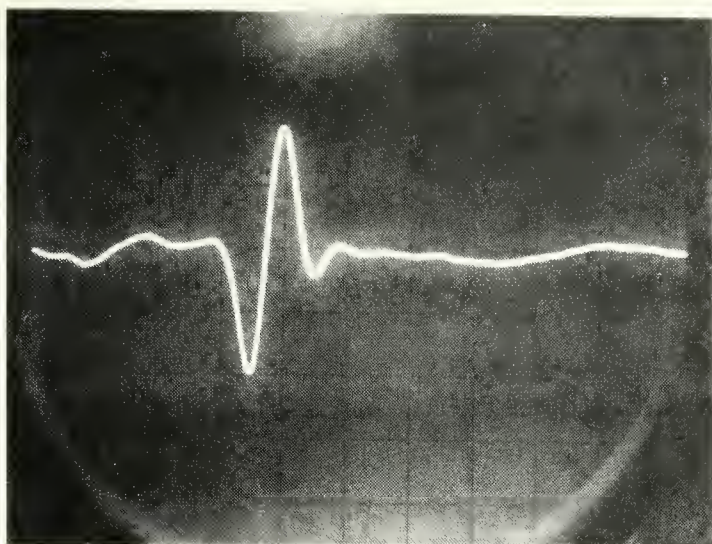


Fig. 4

0.2 sec/cm

0.2 volts/cm

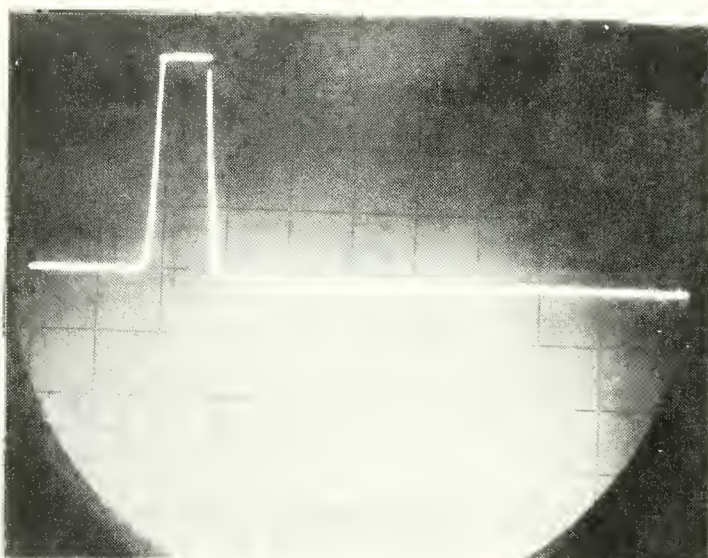


Fig. 5

10 msec/cm

2 volts/cm

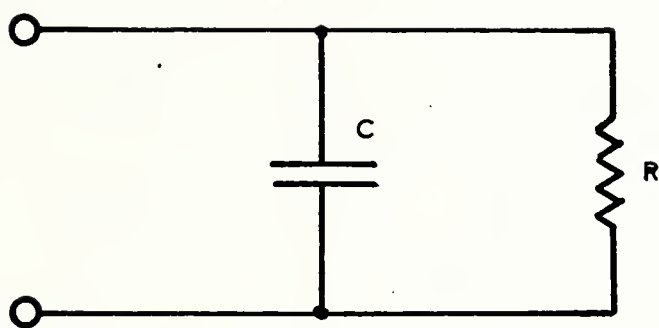


FIGURE 6
PIEZOELECTRIC
TRANSDUCER
EQUIVALENT CIRCUIT

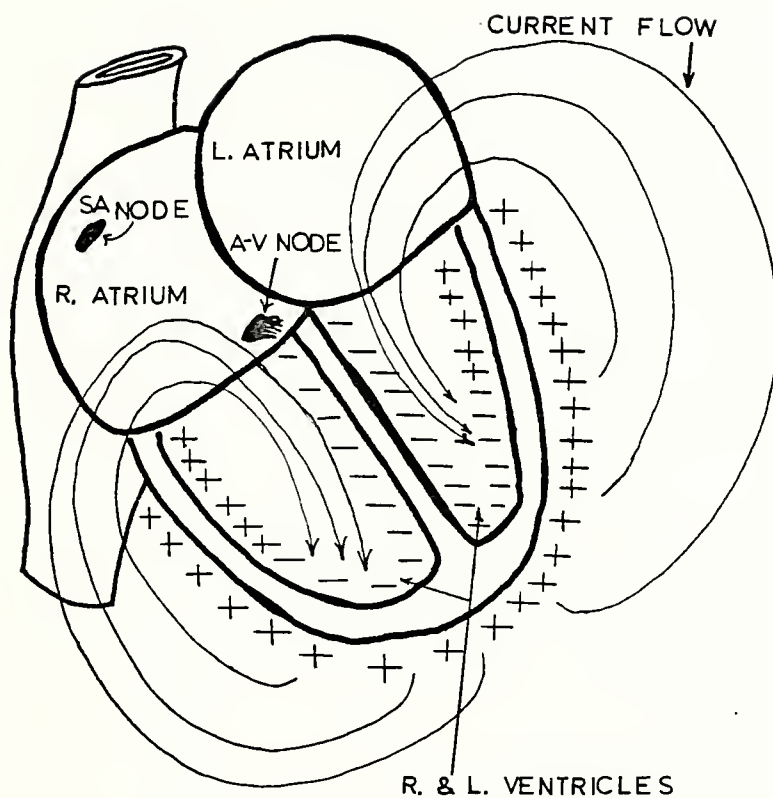
IV. EXPERIMENTAL RESULTS

A. ELECTROCARDIOGRAM SECTION

Electrical activity of the heart is initiated by depolarization of the sino-atrial node (Figure 7) resulting in contraction of the muscles surrounding the atria. This electrical activity is transmitted to the atrio-ventricular node which in turn transmits the heart action potential wave to the ventricles through the A-V bundle. Immediately following their depolarization, the atria and ventricles repolarize. Depolarization and subsequent repolarization of the heart cause current flow around the heart and surrounding tissues and may be detected on the surface of the body (Figure 7). It is the potential difference due to this current flow which is sensed by ECG electrodes.

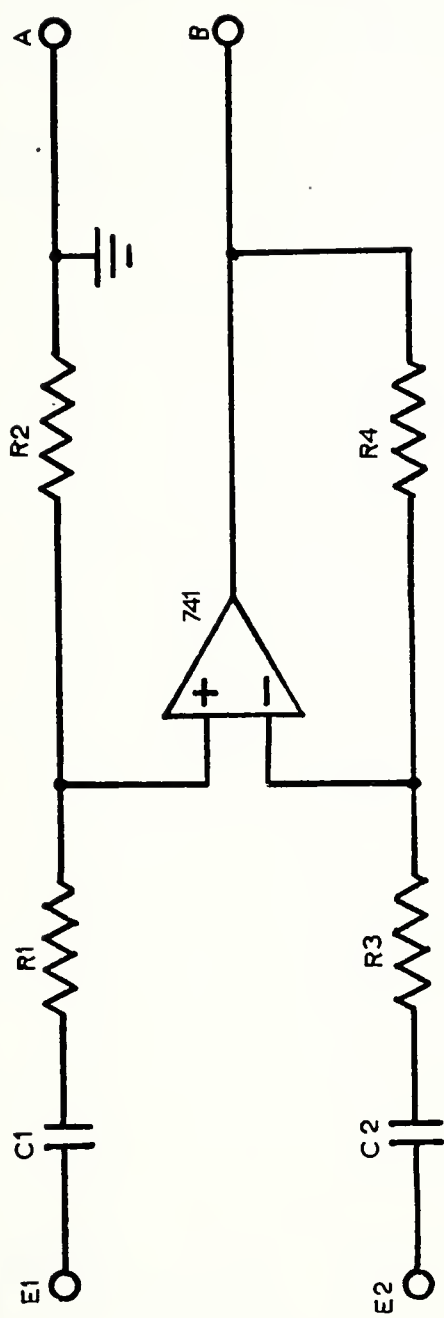
The chest electrodes used to sense an ECG signal, however, are not analogous to two probes applied to an electronic circuit to measure a potential difference. Current conduction in tissue is ionic; that is, it is achieved by the migration of positive and negative ions. In order to measure bioelectric activity in tissue, it is necessary to shift from ionic conduction to electronic conduction at a tissue - electrode interface. There are many effects which must be considered at this tissue-electrode interface. Electrical stability, D.C. offset potential, and electrode noise are several factors which must be considered in the design of electrodes and in the selection of amplifiers for biomedical monitoring applications.

Consistent with present day practice, an AC coupled, high input impedance, differential amplifier with high common mode rejection was chosen as a suitable configuration and was designed (Schematic 1) and tested.



HEART ELECTRICAL ACTIVITY

FIGURE 7



SCHEMATIC 1
ECG DIFFERENTIAL AMPLIFIER

R1 - 2K

R2 - 3.9M

R3 - 2K

R4 - 3.9M

Operational Amplifier;

C1 - 1uF

Fairchild uA741

C2 - 1uF

E1, E2 - Beckman ECG Electrodes

A typical physiological measurement configuration (Figure 8) illustrates the importance of common signal rejection. Without common mode suppression, 60 Hz. and other magnetically and inductively coupled noise can blank an ECG signal only millivolts in magnitude. The common mode rejection ratio (CMRR) of a differential amplifier is defined as its ability to reject common mode signals. The common mode rejection ratio of the DMS differential amplifier is calculated below:

Differential Signal

voltage input = 0.001 volts

voltage output = 0.810 volts

Common Signal

voltage input required to yield

0.810 volts output = 6.8 volts

voltage output = 0.810 volts

$$\text{CMRR} = 20 \log_{10} \frac{\text{common mode input}}{\text{differential mode input}}$$

$$= 20 \log_{10} \frac{6.8}{0.001} = 76.7 \text{ dB}$$

Results with this amplifier were satisfactory with resting subjects. Exercising subjects, however, produced myoelectric artifacts of amplitude sufficient to obliterate the ECG waveform.

A first attempt to suppress myoelectric artifacts was to position the electrodes on the diver's body where the least artifact would be encountered, i.e. over areas of least muscle tissue concentration. Experiments on exercising subjects indicated that the electrode configuration of Figure 9 yielded minimum artifact pickup. However, even with this electrode placement, hard chest muscle strain still produced occasional myoelectric artifacts of amplitude as great as the ECG waveform.

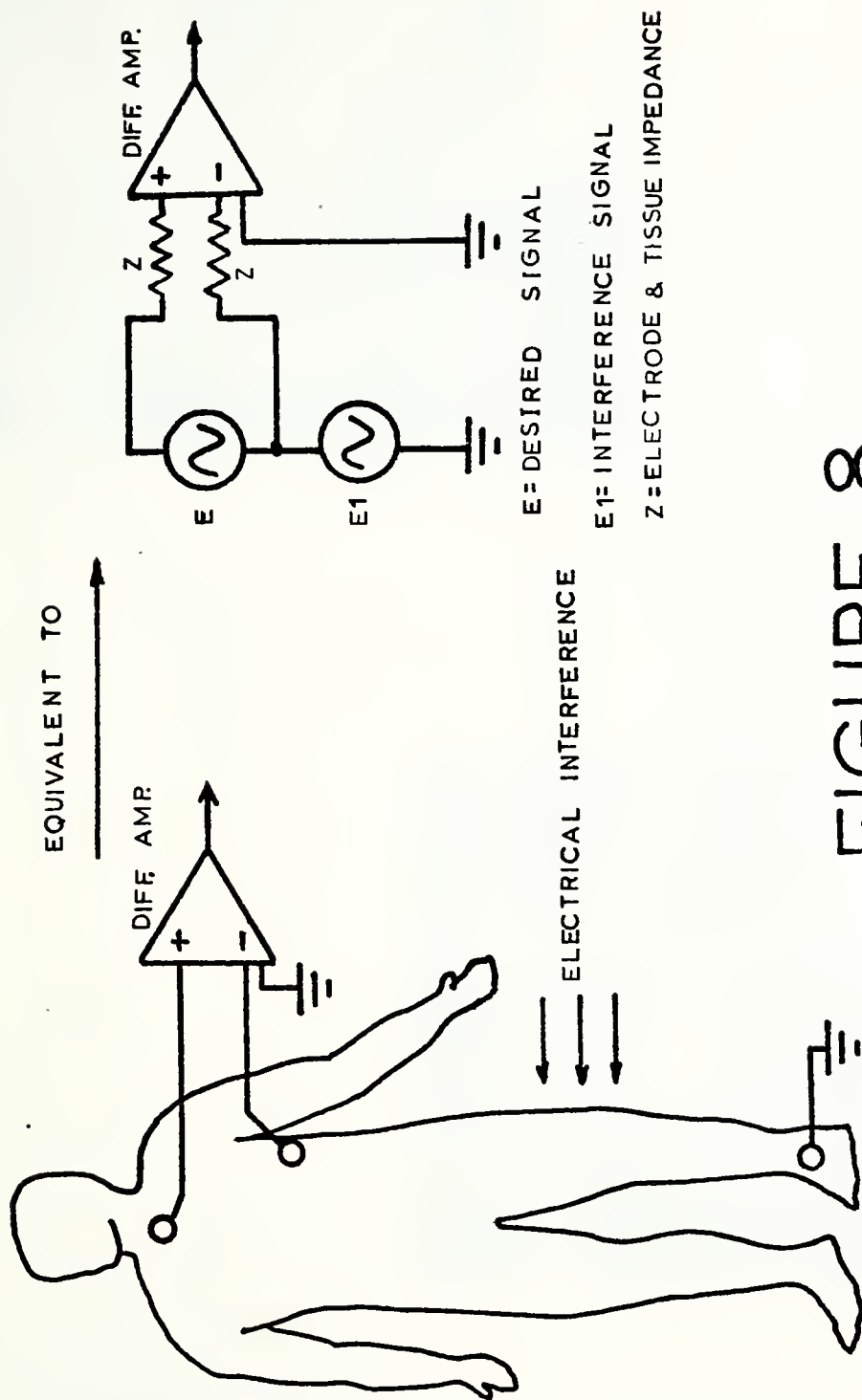


FIGURE 8
PHYSIOLOGICAL MEASUREMENT

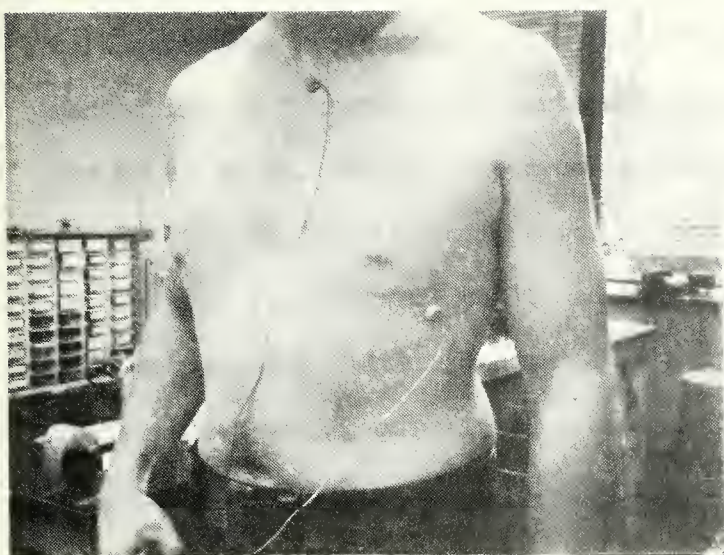


Fig. 9

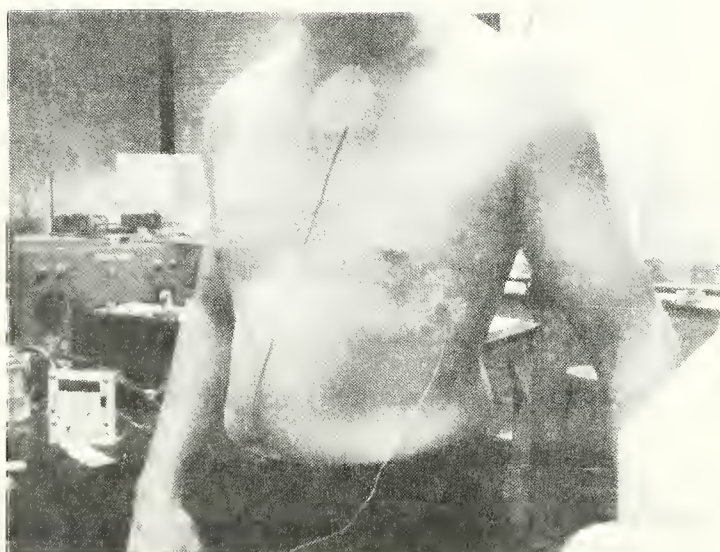


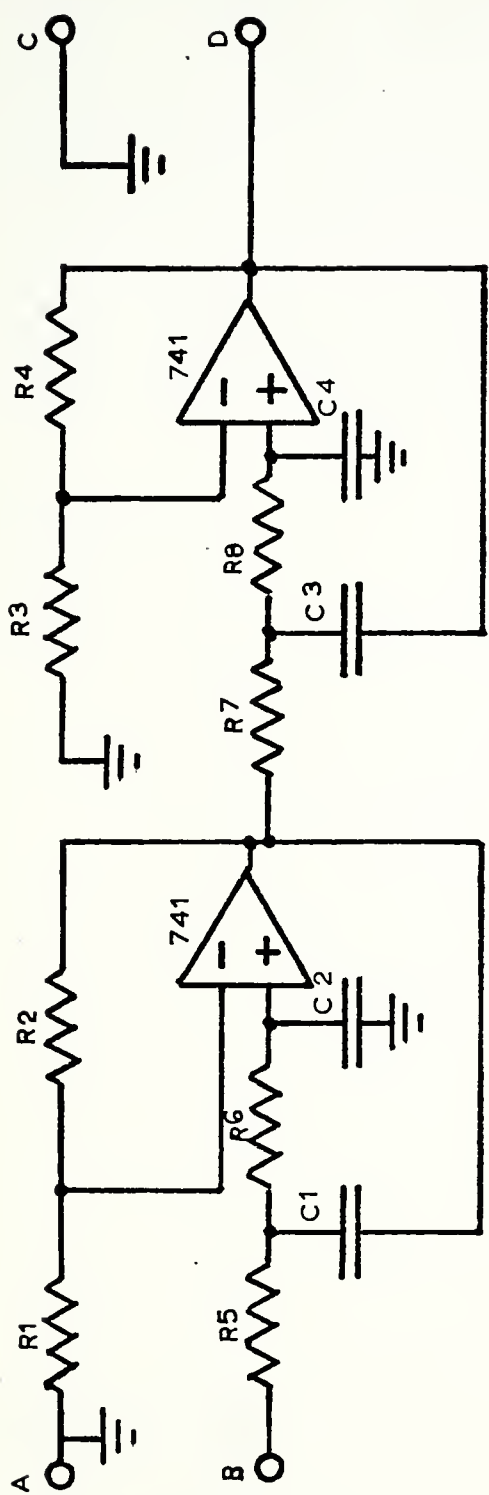
Fig. 10

The next step, therefore, was to design a filter stage to follow the ECG amplifier. A spectral analysis of several subjects' ECG and myoelectric waveforms was carried out. The frequency spectrum of ECG waveform ranged from 0.5 hertz to 80 hertz with maximum power spectral density in the 20 to 30 Hz. range. The myoelectric signals ranged from several Hz. to over 100 Hz. with maximum power in the 40 to 50 Hz. range.

Several filters were built and tested. An active, four pole, low pass Butterworth filter (Schematic 2) proved most effective in suppressing artifact while maintaining a well-defined QRS complex.

The effectiveness of the differential amplifier/filter combination was tested on exercising subjects. A dual trace storage oscilloscope simultaneously monitored the ECG/myoelectric waveform at the output of the differential amplifier (bottom trace) and the output of the amplifier/filter combination (top trace). As indicated in Figures 11 through 13, good myoelectric suppression was achieved. A gain versus frequency curve of the amplifier/filter signal conditioner is presented in Figure 14. In order to waveshape the ECG signal into a waveform suitable for turning on a PNP transistor switch, a two stage clipping/amplifier circuit was designed and built. The desired trigger waveform (Figure 5) was achieved by a circuit (Schematic 3) which successively clips and amplifies the R portion of the QRS complex (Figure 1). Under all conditions of subject activity a clean artifact-free pulse (Figure 5) was produced by the combined amplifier/filter/waveshaping circuit.

At this time a system was constructed which would allow testing of the DMS concept and the components designed to date. An audio oscillator with trigger circuit and loudspeaker (Figure 15) was constructed to simulate the sonar transmitter section of the DMS. Subjects were first "dry-tested" doing push ups, jogging, and bicycling. An audio "beep" was



SCHEMATIC 2

LOW PASS FILTER

R1 - 10K
R2 - 12.4K
R3 - 10K
R4 - 1.5K
R5 - 3K
R6 - 3K
R7 - 3K
R8 - 3K
C1 - 1uF
C2 - 1uF
C3 - 1uF
C4 - 1uF

Operational Amplifiers;

Fairchild uA741

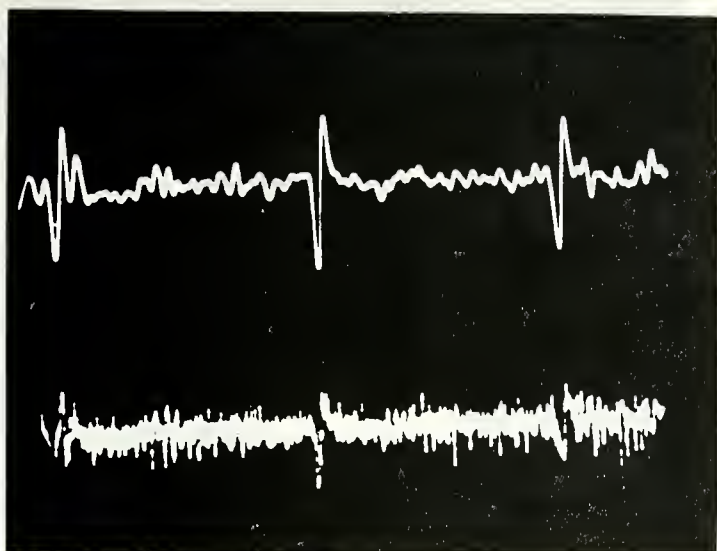


Fig. 11

0.5 sec/cm

0.5 volts/cm (top)

Maximum isometric force on chest muscles.

Figures 11 - 13:

Bottom trace is the ECG signal at the output of the differential amplifier. Top trace is same signal at output of filter.

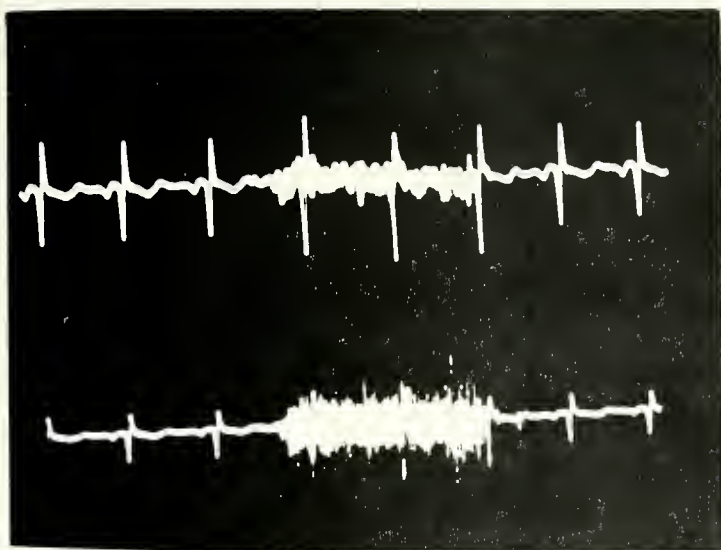


Fig. 12

0.2 sec/cm

0.5 volts/cm

One second duration hard strain.

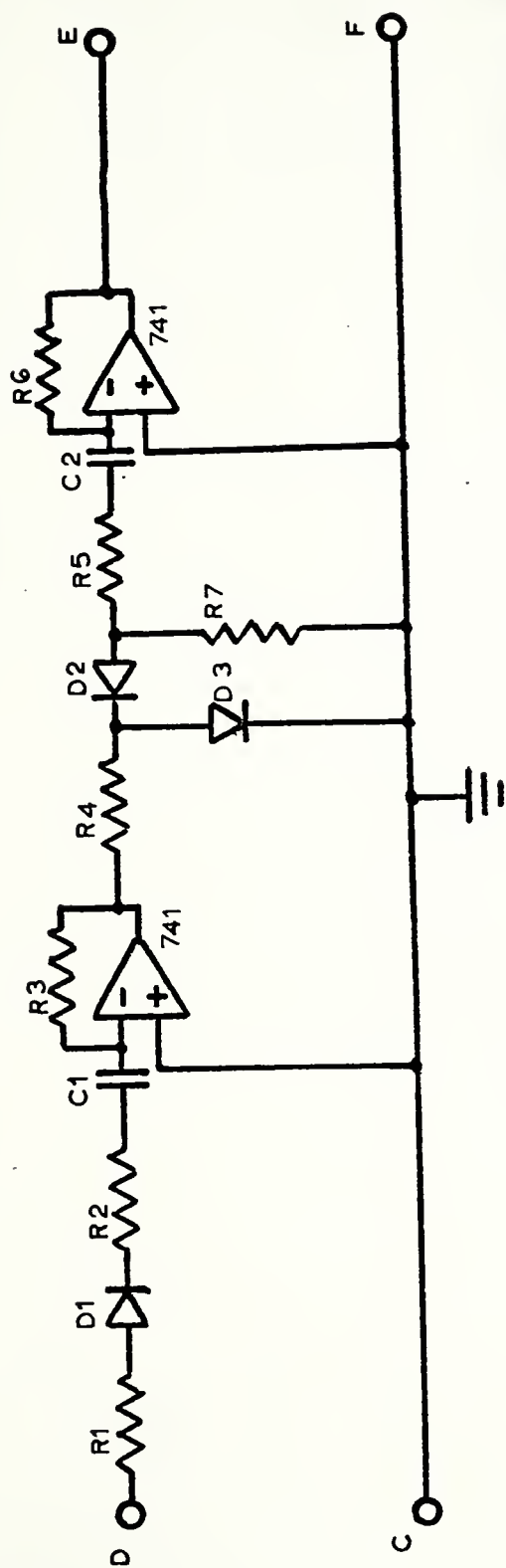


Fig. 13

0.5 sec/cm

0.5 volts/cm

Maximum isometric force on chest muscles.



SCHEMATIC 3

WAVESHAPING CIRCUIT

R1 - 150

R2 - 1K

R3 - 6K

R4 - 1K

R5 - 1K

R6 - 100K

R7 - 1M

C1 - 1uF

C2 - 1uF

D1 - 1N276

D2 - 1N276

D3 - 1N276

Operational Amplifiers;

Fairchild uA741

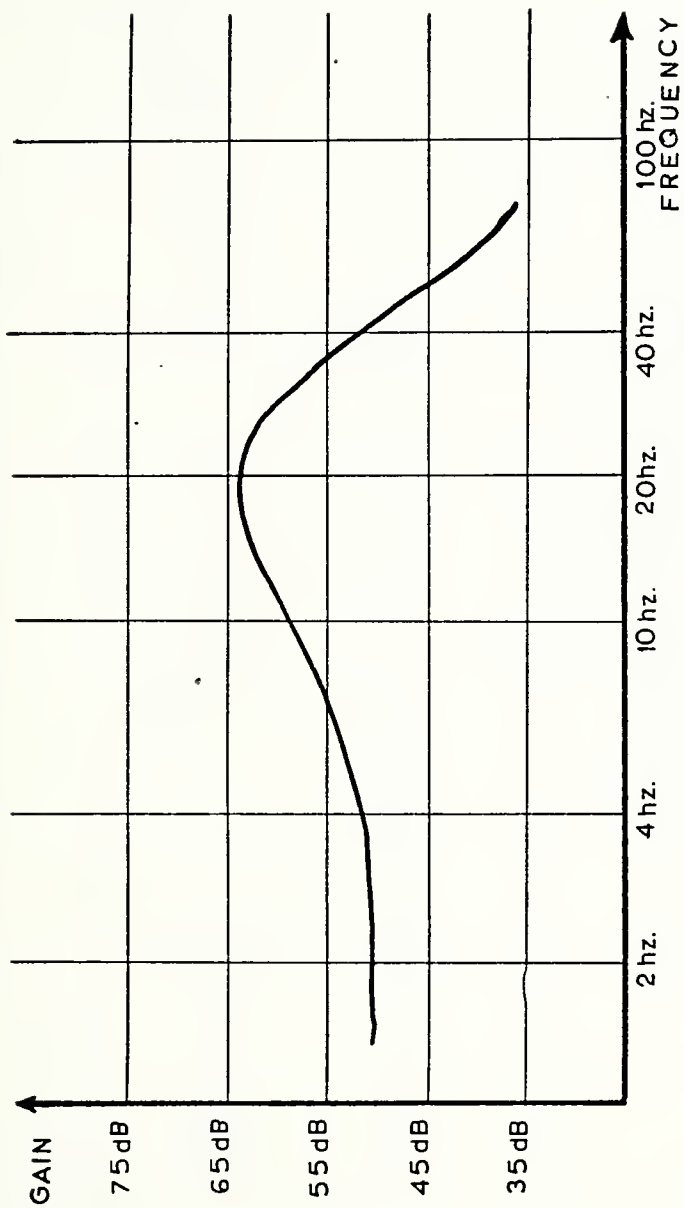


FIGURE 14
ECG AMPLIFIER/FILTER
GAIN VS. FREQUENCY

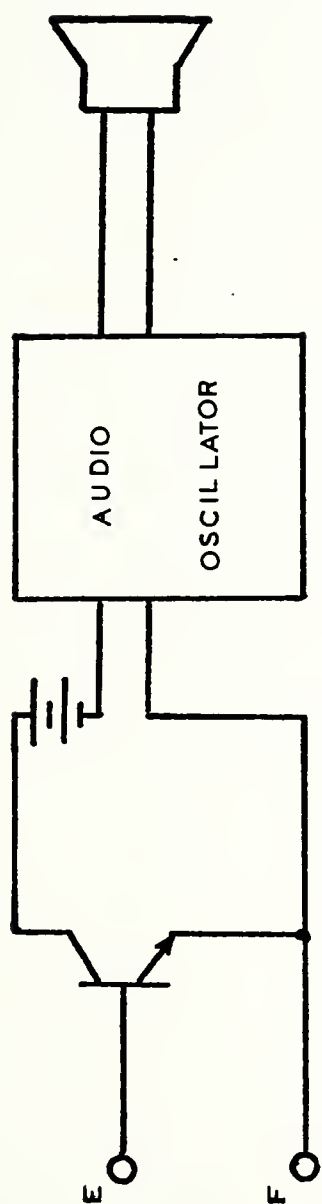


FIGURE 15
TEST CIRCUIT

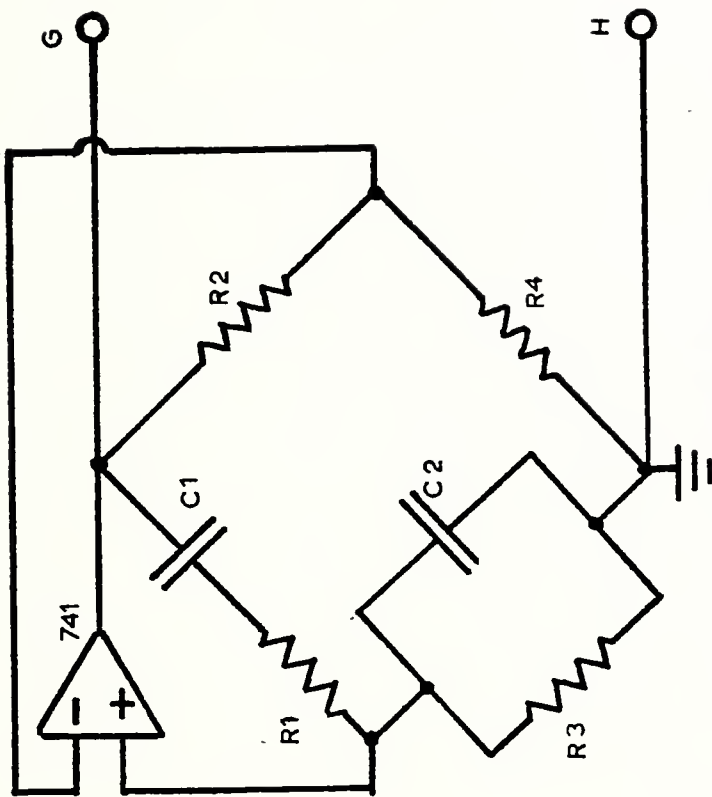
produced from each heart beat. No artifact triggering was noted. A problem was encountered, however, with the method of securing the chest electrodes to the subjects. Friction with subjects' clothing was often sufficient to cause movement at the electrode-paste-skin interface. Any movement of electrode, paste, or skin relative to each other generated a strong spike causing false triggering of the audio oscillator. The best remedy without obtaining a different type of electrode was to cover the electrode and lead wire with a three-inch circular adhesive disc (Figure 10) which presented a smooth exterior surface and was less subject to being moved by clothing.

Subjects were next tested in fresh and salt water with satisfactory results. Again, however, the electrodes had to be positively sealed against water seepage into the electrode-paste-skin interface area. Sealing was achieved by using liberal amounts of commercially available waterproof adhesive tape. The adhesive tape was effective for limited durations and the sealing of underwater electrodes remained a major problem. Procurement of a high quality, flexible waterproof adhesive tape which is impervious to salt water will eliminate this problem. Availability of such tape is being investigated.

B. SONAR SECTION

Simplicity, small size, and maximum power output utilizing the system's two nine volt batteries in split supply configuration were major considerations in the design of the transmitter section.

Several oscillators were considered, and a Wien bridge phase shift oscillator (Schematic 4) utilizing a uA741 operational amplifier was chosen due to its small overall size and small number of components. It was also deemed suitable for selective frequency operation in that several



SCHEMATIC 4
WIEN BRIDGE OSCILLATOR

R1 - 390

R2 - 4.4K

R3 - 390

Operational Amplifier;

R4 - 2K

Fairchild uA741

C1 - 0.0068uF

C2 - 0.0068uF

different phase shifting circuits could be hard-wired into each DMS transmitter. Frequency could then be accurately and rapidly selected with an externally accessible multi-position switch. Thus, each of a group of divers could simultaneously transmit on different frequencies in the 40 kHz. band.

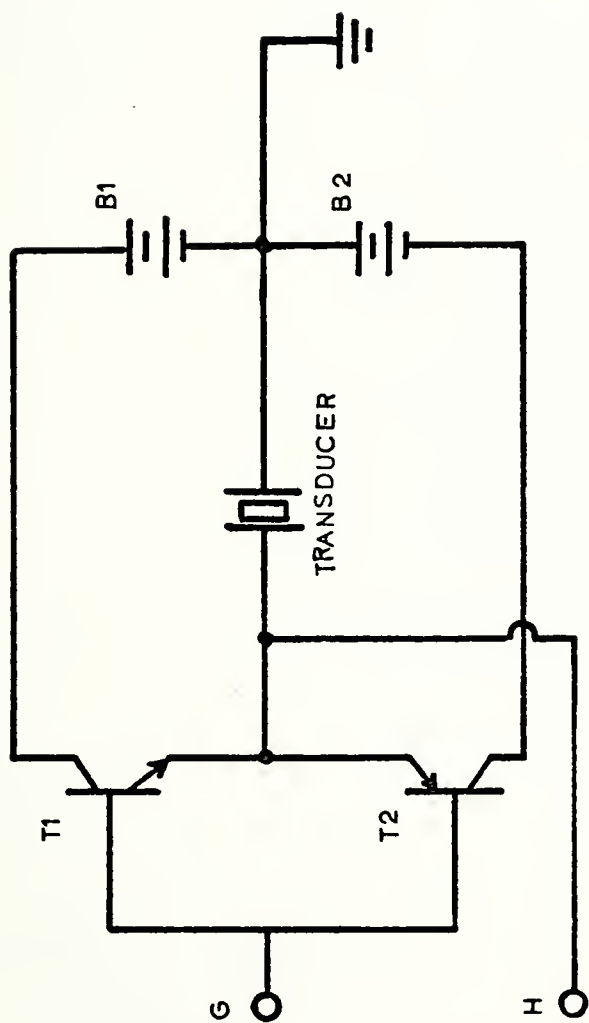
The power amplifier stage was also designed to meet the requirements of small size, few components, and maximum power output from two nine volt batteries in split supply configuration. Since the acoustical power output of a piezo-ceramic transducer is proportional to the voltage across the device, maximum voltage swing across the transducer was desired and the configuration in Schematic 5 was built and tested. At 40 kHz., with a transducer impedance of 150 ohms, a voltage swing of 17 volts was achieved yielding a power input to the transducer of 0.96 watts. The voltage waveform across the transducer is presented in Figure 16.

The complete transmitter unit was mounted inside a watertight container (Figure 18) and tested in the sonar tank. A calibrated receiving hydrophone was utilized to calculate effective source level. An actual source level of 0.8 watts was indicated. Figure 17 is the voltage waveform generated by the receiver hydrophone.

The transmitter was next tested in the NPGS swimming pool. The transmitted signal was monitored on an oscilloscope. The transmitter appeared to be quite omnidirectional and radiated equally well with the transducer in any attitude.

C. COMPLETE DMS TRANSMITTER

The trigger circuit (Schematic 6) was installed on the sonar transmitter. The ECG section and transmitter were wired together and mounted in the watertight container. The first test of the complete system was



SCHEMATIC 5
POWER AMPLIFIER

T1 - 2N5449

T2 - 2N5447

B1 - 9v

B2 - 9v

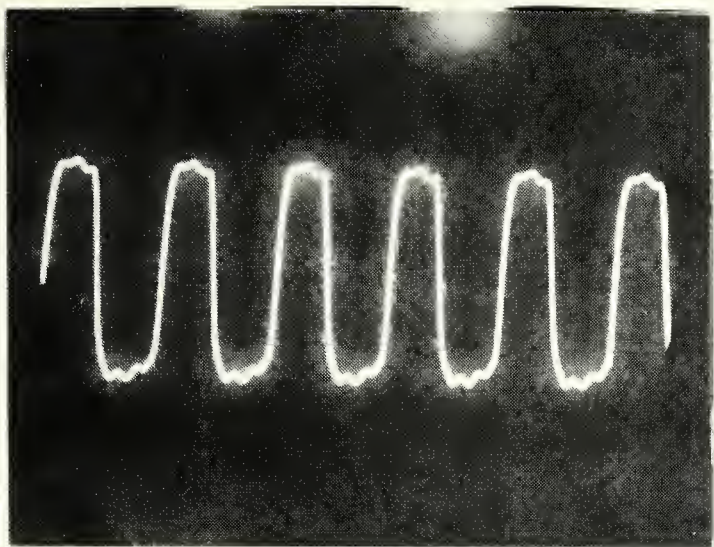


Fig. 16

10 μ sec/cm

5 volts/cm

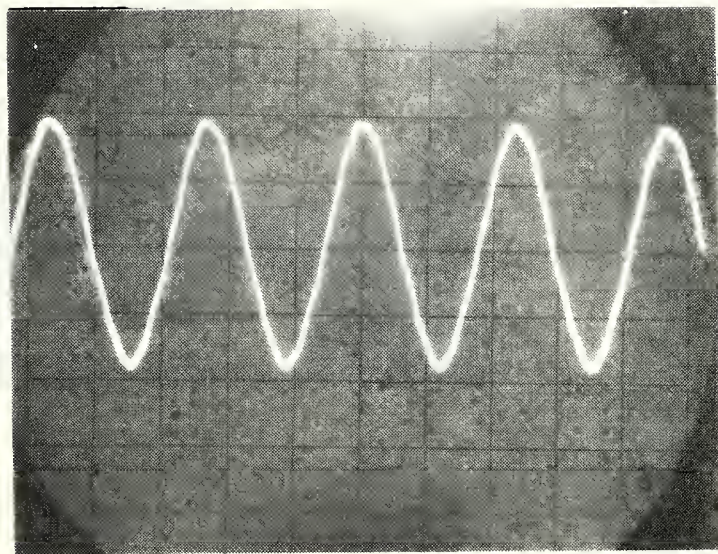


Fig. 17

10 μ sec/cm

2 millivolts/cm

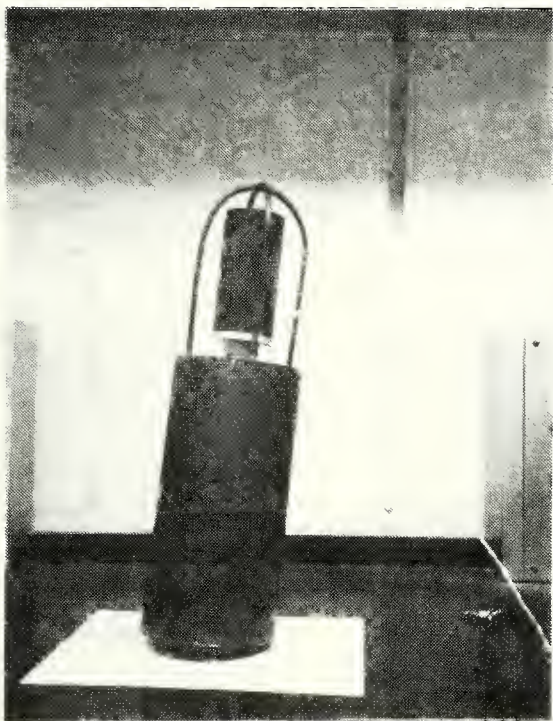
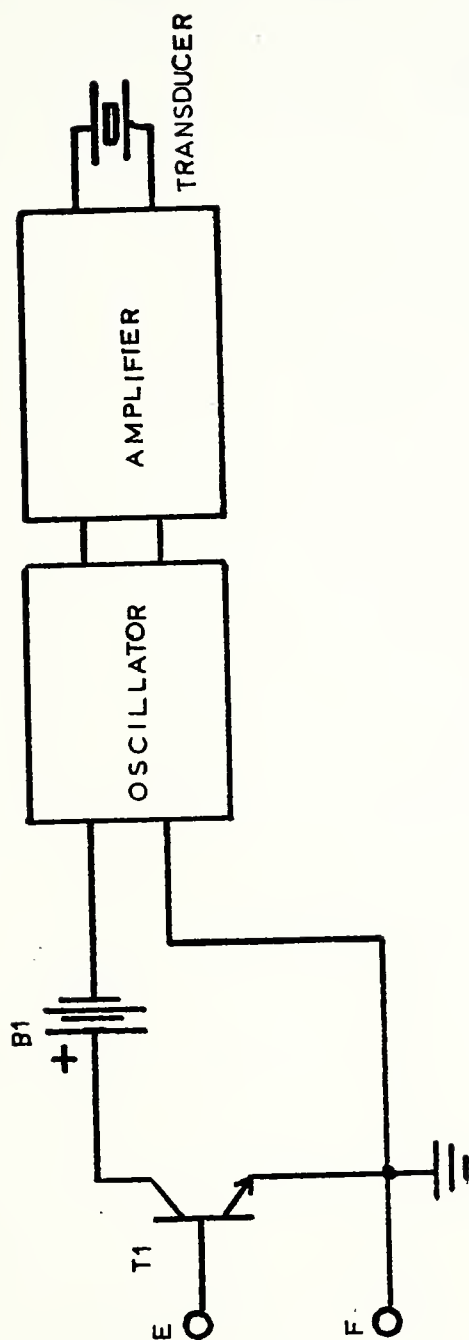


Fig. 18



SCHEMATIC 6
TRIGGER CIRCUIT

T1 - 2N3404

B1 - 9v

in the pool. Poor electrode sealing caused intermittent operation and false triggering. At a second trial, liberal use of waterproof adhesive tape achieved a good seal. The system worked satisfactorily while the subject performed a variety of activities ranging from vigorous swimming to sitting on the bottom. Heart rates from 38 beats per minute, with the subject holding his breath, to 180 beats per minute after vigorous swimming were recorded.

The system was next tested in the ocean. The test was conducted in the quite noisy Monterey Harbor. At a range of 350 yards the signal was still strong but was partially blanked by heavy interference from a local radio station, KMBY, whose antenna is located only several miles down the beach. The receiver also picked up a variety of acoustic noise from harbor activity and from breakers 100 yards away. An active bandpass filter installed between hydrophone and receiver should solve the problem of radio frequency interference which results when the hydrophone and transmission line between hydrophone and receiver act as an antenna to introduce rf into the receiver. The acoustic noise, although audible, remained well below the signal level even at a range of 350 yards. The waterproof adhesive tape did not maintain a seal for as long in the cold sea water as in the heated fresh-water pool.

V. CONCLUSION

A. THE DIVER MONITOR SYSTEM CONCEPT

The purpose of this work was to investigate the feasibility of a practical DMS. It has been investigated and the concept is considered practical and feasible. As tested in its simplest form, it does provide a method of tracking and ascertaining the well-being of untethered divers.

In addition, it is noted that the unit could easily be modified to include several higher levels of functional capability. These functions include monitoring of several selected diver physiological parameters, and communication from diver to surface utilizing the DMS transmitter unit.

The capability to communicate with the DMS transmitter unit is practically built-in. Basic communication capability could be achieved by inclusion of an emergency interrupt which would allow the diver to manually switch the DMS transmitter into CW mode thereby indicating an emergency situation. On a slightly more complex level, code transmission capability could be achieved by fitting the diver's mouthpiece with contacts allowing him to transmit code to the surface.

A DMS with logic circuit-generated warning-signal transmission when physiological parameters are exceeded, would automatically signal topside of an out of tolerance condition allowing immediate diver recovery.

B. DIVER MONITOR SYSTEM HARDWARE

The DMS signal conditioner (differential amplifier, filter, clipping circuit) is considered satisfactory. The sonar transmitter section is also considered adequate and of sufficient power. The entire system is presently being optimized and miniaturized by Lt. Steere.

The greatest problem with the system as tested is the man-electrode interface. The electrodes must be reliably sealed against water intrusion and must be protected from impact and movement.

Several types of electrodes presently being utilized by NASA for ECG recording in space flight have been suggested as being possibly suited to DMS application and will be investigated as part of the continuation of this work. A continuation of the development of a practical DMS will also include the design and construction of a DMS receiver capable of monitoring several divers simultaneously. A properly designed receiver will increase the system's effective range and effectively suppress rf interference. With the design of a good receiver and the development of a convenient and reliable electrode system, the major hardware problems of DMS will have been solved.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A system is presented which allows continuous monitoring of a free-swimming diver. The Diver Monitor System (DMS) employs a diver-carried acoustic transmitter which transmits pulses synchronized with the diver's heartbeat. Surface personnel are able to monitor the diver's general physical state as indicated by his heart rate and, by directional homing with Navy hand-held sonar, can locate and recover divers in zero visibility conditions. A continuous signal may be transmitted automatically in the		

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the diver's heart stops or exceeds preset limits.

The diver's electrocardiogram signal is picked up by chest electrodes, amplified, filtered, and waveshaped into a trigger pulse which activates a one watt 40 kHz. sonar transmitter.

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